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A new flood risk assessment framework for evaluating the effectiveness of policies to improve urban flood resilience

Michael Hammond, Albert S. Chen, Jelena Batica, David Butler, Slobodan Djordjević, Philippe Gourbesville, Nataša Manojlović, Ole Mark, William Veerbeek

Abstract

To better understand the impacts of flooding such that authorities can plan for adapting measures to cope with future scenarios, we have developed a modified Drivers-Pressures-State-Impact-Response (DPSIR) framework to allow policy makers to evaluate strategies for improving flood resilience in cities. We showed that this framework proved an effective approach to assessing and improving urban flood resilience, albeit with some limitations. This framework has difficulties in capturing all the important relationships in cities, especially with regards to feedbacks. There is therefore a need to develop improved techniques for understanding components and their relationships. While this research showed that risk assessment is possible even at the mega-city scale, new techniques will support advances in this field. Finally, a chain of models engenders uncertainties. However, the resilience approach promoted in this research, is an effective manner to work with uncertainty by providing the capacity to cope and respond to multiple scenarios.

Keywords

DPSIR; flood risk management; mitigation measures; resilience; science-policy; urban development.

1 Introduction

Flood risk management is a significant challenge for cities, with widespread impacts on society, the economy, and the environment. Several trends suggest that these challenges will grow. First, the world's urban population is projected to grow from 4.0 billion to 6.3 billion by 2050, leaving more people exposed to flooding (Jongman et al. 2012, United Nations, 2013). This growth increases demand for land, and it has been estimated that between 2000 and 2030, the total urban surface area will increase by over 1.5 million km^2 (Seto et al., 2011). This will increase the risk of flooding through reduced infiltration and faster hydrological response, and the loss of natural storage areas (Ramachandra et al., 2012). Second, economic growth increases the value of exposed assets. Third, climate change is expected to cause more extreme precipitation in many parts of the world (Kunkel et al., 2013). Rising sea levels will also leave more people exposed to coastal flooding (Hallegatte et al., 2013; Aerts et al., 2014).

These changes are uncertain, and it is imperative that planners and decision makers can develop policies to address a range of possible futures. Sörensen et al. (2016) have argued for the need to re-think urban flood risk management, taking account not only climate change, but also interlinking sectors such as energy and water, and the role of actors, institutions and stakeholders. While we concur with this approach, practical frameworks for analysing these problems are limited. Some authors have focused on the concept of robustness in flood risk management (Mens et al., 2011), others have chosen to focus on resilience (Aerts et al., 2014). Butler et al. (2017) have developed an approach that combines sustainability, resilience and reliability, which provided a definition for resilience for urban water system, focused on service failure. Here, we take a more expansive view of urban flood resilience, which we define as "the ability of an urban system exposed to a flood hazard to resist, absorb, accommodate, adapt to, transform and recover from the effects of flooding in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions". This is definition is adapted from UNISDR (UNISDR, 2009).

There is a strong literature that deals with approaches to the assessment of the risk and resilience of urban systems under static conditions. Mugume and Butler (2016) developed an approach that evaluated the resilience of urban drainage systems, under a particular configuration, considering their functionality in relation to flood volumes and durations. Kotzee and Reyers (2016) developed a resilience index constructed from data on factors such as civic involvement, access to transport and housing types. However, in this case, urban changes were not considered. Bowering et al. (2014) and Peck et al. (2014) developed and applied a methodology for the assessment of flood risk incorporating climate change, with a focus on municipal infrastructure, but did not incorporate urban change. Numerous studies assess flood risk under climate change, assuming changes to rainfall intensity and sea level (Budiyono et al., 2015; Wahl et al., 2015).

Some interesting global approaches can provide an indication of the overall trends in flood risk and urban resilience, but they cannot be useful for policy makers looking at the finer scale of individual cities or districts (Muis et al., 2015; Wing et al., 2018). As Eakin et al. (2017) point out, the urban resilience agenda should also incorporate the "social-political infrastructure" that includes the norms, policies, and values that shape cities.

Djordjević et al. (2011) proposed a Drivers-Pressures-States-Impacts-Response (DPSIR) logical framework for assessing urban flood risk management strategies. The elements of this framework could not be specified a priori, and real case studies were needed to understand the elements and relationships. This framework was therefore developed in detail working with seven European and Asian Case study cities reflecting a diversity of socio-economic conditions, climates, decision-making processes and urban forms. These cities were Barcelona, Beijing, Dhaka, Hamburg, Mumbai, Nice and Taipei. In this paper we describe a new framework, building on the limitations observed from the literature review, identifying the strengths and weaknesses of our approach, while proposing routes for future research. This paper cannot deal in detail with the technical components of each element of the framework, and so references are made to other publications.

2 Literature review

The DPSIR Framework is an approach that has been used to understand and evaluate the state and performance of various social-environmental system. The DPSIR framework was developed by the European Environment Agency (EEA, 1999), although its genesis can be seen in relation to forerunner frameworks such as the Stress-Response framework developed by Statistics Canada in the 1970s, and was later extended as the Pressure-State-Response (PSR) framework (OECD, 1994). The DPSIR framework has been applied to many problems such as water resource management (Mysiak et al., 2005; Pouget et al., 2012), marine ecosystem management (Cook et al., 2014; Mangi et al., 2007), land-use change (Helming et al., 2011), coastal zone management (Pirrone et al., 2005), biodiversity (Omann et al., 2009), and coastal flood risk (Mokrech et al., 2014).

In the field of flood risk management, a literature review identified several examples where the DPSIR (or a modified version) had been developed and applied, either quantitatively, or qualitatively. This review shows there was a wide variety of approaches, with different elements, classifications, and objectives. Many of the differences relate to the classification of drivers and pressures. Harvey et al. (2009) adopted the DPSIR framework to qualitatively assess future flood risk in China. Their aim was to identify the key drivers and potential response measures. They defined drivers to include social-economic changes and climate change scenarios as human and societal pressures or drivers, which have the potential to change either a source (e.g. heavy rainfall), a pathway (e.g. overland and fluvial flows and urban drainage systems), and a receptor (people, assets and infrastructure). As such, they included the development of flood risk infrastructure as a driver. Merz et al. (2010) defined drivers as "any phenomenon that may change the time-averaged state of the flooding system", and also included factors under the control of flood managers, including the construction of flood defence and warning infrastructure, and those outside their control, which includes climate variability, and increased asset values). Conceptually, placing flood defence infrastructure as a driver appears at odds with the original formulation of a driver, which defines them as the "social and economic developments that put pressure on the environment" (EEA, 1999).

Narayan et al. (2013) also adopted the DPSIR framework to assess coastal flood risk, but defined drivers as external to the flood plain, such as climate change and storms. Their approach was coupled with a Source-Pathway-Receptor model to focus on the state. The state embodies the flood plain, flood defences and the physical infrastructure. Impacts include economic losses, and response as any measure to mitigate risk. Confusion over the classification of different elements appears as a factor in some applications of the DPSIR framework (Akmalah and Grigg, 2011).

Ceccato et al. (2011) exploited a DPSIR framework, for its use as a communication tool to support participatory approaches to flood risk management. Their recognition of its use as a communication tool is closer to the original formulation of the DPSIR approach, rather than as an analytical tool. Lewison et al. (2016) indicated the disintegration of data and knowledge between natural and social science remained the main barrier for implementing DPSIR as a quantitative assessment framework, which could also be regarded as an opportunity to release the full potential of the DPSIR framework.

Some authors simplified their approaches. Lee at al. (2013) ignored drivers for being too distant from the concerns of planners. Chen et al. (2015) adopted a simplified approach, developing a simple index for each factor, based on one variable. This methodology is attractive for its simplicity but cannot be used to understand the complex web of interrelations in the flood management system.

This brief review has shown that while other authors have adopted a version of a DPSIR approach, there is a need to overcome several problems: (1) A clear understanding of the relationships between the elements, and consistent definitions (2) the need to be sufficiently rich to capture the key processes in urban flood risk management, and (3) the ability to be applied in at least a semi-quantitative manner.

3 The enhanced DPSIR Framework

The new framework is a modified form of the DPSIR framework, which aims to allow researchers to explore environmental management questions under a range of scenarios, to investigate the effects of change, and to evaluate the effectiveness of responses to address these questions. In this framework, the Drivers, Pressures, States, Impacts and Responses are linked through a modelling chain representing a flow of information and data (Figure 1).

The framework incorporated several key principles. First, it is a flexible approach that can be applied to real-world urban examples with various geographical, environmental and socioeconomic conditions. The framework is also flexible in that any model of the framework can be replaced and improved. Second, present and future states are considered, by considering changes to urban form, and climate change among other pressures and drivers. Third, the approach is necessarily interdisciplinary, bringing together economists, engineers, architects and social scientists. Finally, existing policies and legal frameworks have been considered.

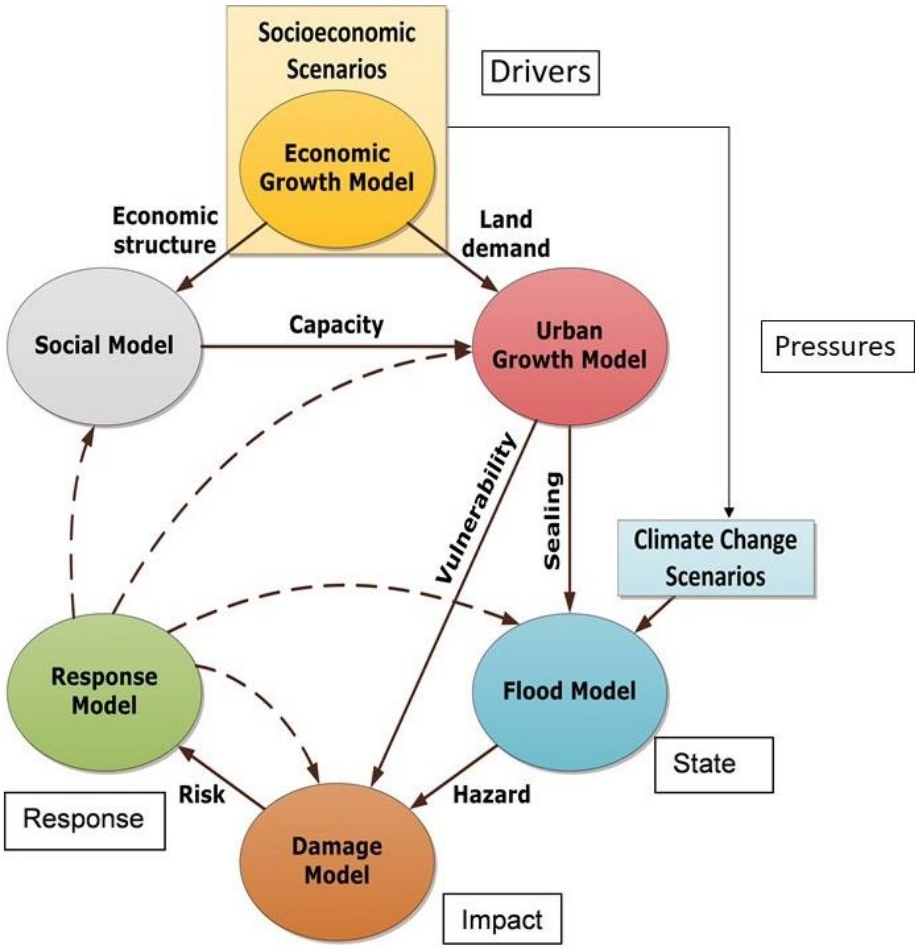


Figure 1. The DPSIR framework

3.1 Drivers and pressures

In the context of urban flood risk management, there is a significant challenge of differentiating between drivers and pressures. In the case of urban flooding, economic and demographic changes, including population growth are the "social and economic developments that put pressure on the environment". However, changes to the urban fabric, such as urban sprawl and densification might be considered the pressures that are placed on the environment.

The approach to addressing anthropogenic climate change and its impacts are also complicated. The emission of greenhouse gases (GHG) can be seen as driven by increased population, which affects demand for energy, food and changes in land use. Others drivers of emissions may include institutions, urbanisation, trade, and culture (Rosa and Dietz, 2012). Increased GHG emissions create environmental pressures, affecting atmospheric concentrations of GHG, resulting in a changed radiative forcings, and increased global temperatures, and may lead to an intensification of precipitation extremes (O'Gorman and Schneider, 2006). In urban flood risk management, the key interest in climate change is the extent to which it affects extreme precipitation and sea levels (where relevant). “Climate change” is not a single phenomenon that can be categorised as driver, a pressure, or a state.

In our framework, we rely upon the original definition of drivers and pressures, where drivers are the “social and economic developments that put pressure on the environment”. Four drivers and two pressures have been considered in this framework, and given in Table 1.

Table 1 - Drivers and Pressures

Drivers	Pressures
• Economic growth and structural change • Population growth • Demographic change (including changes to the age profile) • Changes to adaptive capacity	• Urban growth • Emissions scenarios

3.1.1 Socio-economic drivers

The social-economic drivers primarily consider economic and demographic change. Economic development is incorporated in this framework by considering both the change in size of national or regional economies but also in its structure. This requires a link with population developments. In our application, a model was developed to project economic growth, as well as changes to economic structure (Schlitte, 2013). National growth paths from the Oxford Global Economic Model and IIASA population growth rates from IIASA were used as the starting point (Kurzbach et al., 2013). Regional trends were allowed to deviate from national trends, to create scenarios for regional employment, productivity and output. Table 2 summarises national economic growth trends for Bangladesh. The importance for the framework is to understand how regional economic growth could affect the value of exposed assets. However, a key limitation was the inability to link changes in economic structure with exposure. For example, a service-dominated economy would see a different distribution of assets than a manufacturing-dominated economy.

Table 2. **National growth scenarios for Bangladesh**

	Low growth		Medium growth		High growth	
	2050	Growth rate (%) 2012-2050	2050	Growth rate (%) 2012-2050	2050	Growth rate (%) 2012-2050
GDP (billion US$ 2005 prices)	153	197	366	612	506	886
Total population (million)	214	44	194	31	195	31
Population aged 15-64 (million)	142	49	132	39	131	37
Urban population (million)	81	36	101	84	131	138

The drivers and pressures that affect climate change can be brought together through a set of narratives about possible futures. A set of three Shared Socio-economic Pathways (SSP) have been developed for the Intergovernmental Panel on Climate Change (IPCC) underpin emission scenarios, increased global temperatures and changing precipitation patterns. This framework allows the adoption of shared socio-economic pathways (SSP) which result in Relative Concentration Pathways (RCPs) that have been adopted by the IPCC in the 5th Assessment (van Vuuren et al., 2015).

3.1.2 (Environmental) Pressures

Urban growth was analysed using a spatially explicit modelling framework in which land use and land cover (LULC) changes are a manifestation of implicit drivers derived from time series data (Veerbeek et al., 2015). The models are based on Cellular Automata, a grid of cells existing in discrete states representing LULC classes, where transition rules, developed using a Weight of Evidence approach, determine the likelihood of state changes.

A common factor among the Asian cities is their continuing urbanisation causing substantial densification (Beijing), or suburbanization (East of Mumbai) as well as the development of neighbouring towns. These urban growth results were used to estimate Impervious Surface Ratios (ISR), using an adapted method from Angel et al. (2007) to classify zones. The ISR for Beijing and Dhaka is expected to grow steadily. The ISR for Hamburg is dominated by suburban and rural areas, resulting in substantially lower ISRs with less surface runoff and a lower likelihood of flooding (Figure 2).

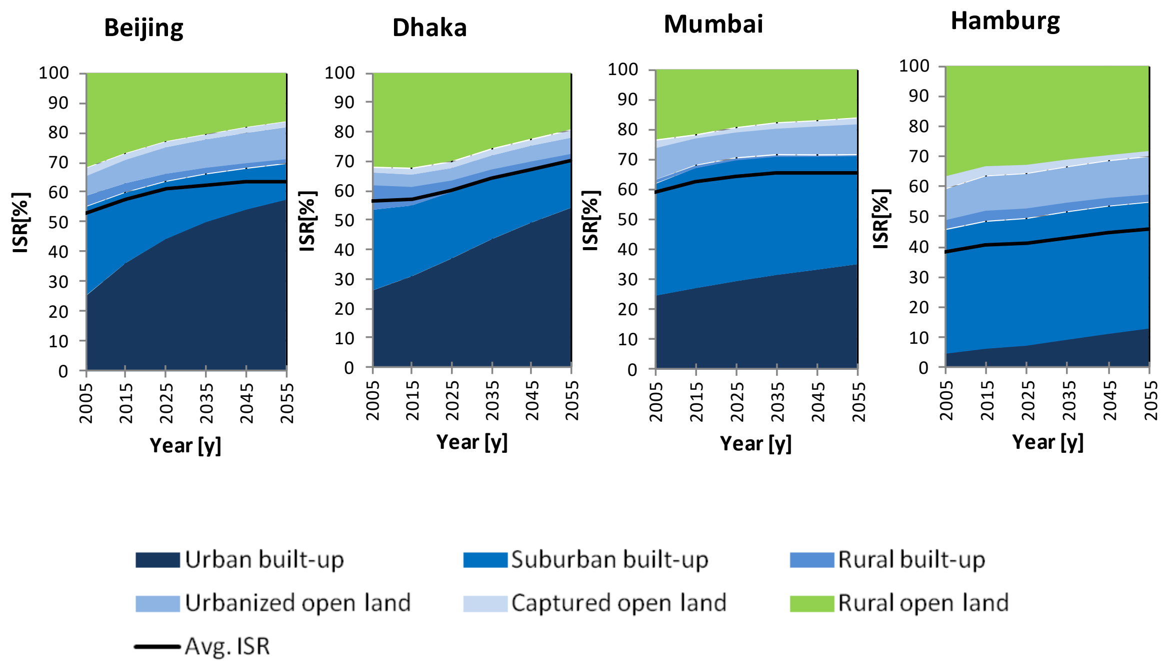


Figure 2. Proportion of impervious cover for Beijing, Dhaka, Mumbai, and Hamburg

3.2 States

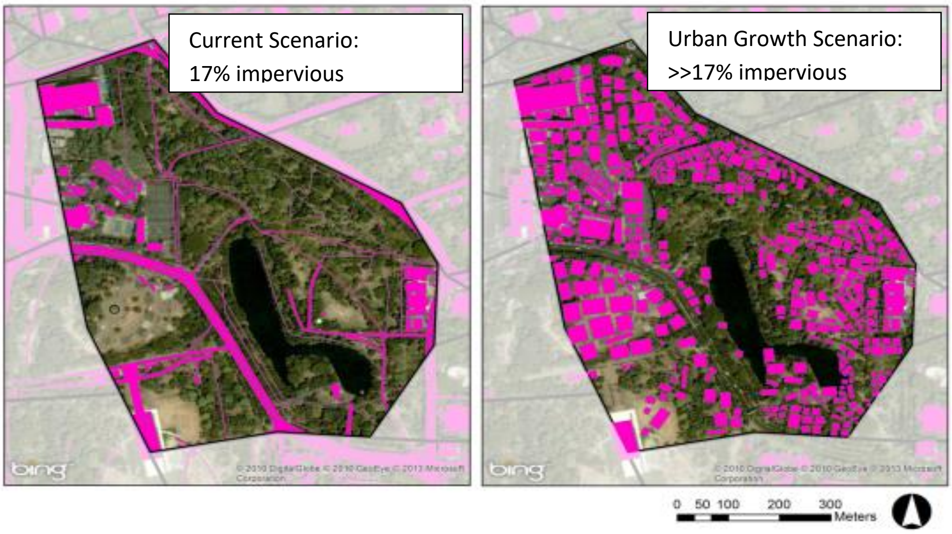
We consider the state of the environment, as it relates to urban flood risk management, as the flood hazards that the city is exposed to, and the extent to which the infrastructure, which includes urban drainage systems and flood embankments can manage these pressures.

3.2.1 Extreme precipitation scenarios

The state of flood hazard is partially a result of the pattern of extreme precipitation and sea levels, which are influenced by the drivers and pressures outlined in Section 3.1. Scenarios were derived from existing studies or from nationally adopted practices, typically by applying 'uplift' factors to amend rainfall scenarios. For example, in Barcelona, rainfall intensities were increased by 12% for the 10-year return period event, and 15% for the 100-year event, for 2050. It is recognised that this simplistic approach may overlook the more complex extreme precipitation trends (Ban et al., 2015). Furthermore, no link was made between urbanisation and extreme precipitation through urban heat island effects (Pathirana et al., 2014).

3.2.2 Urban Flood Hazard Modelling

The flood hazard is best described by state-of-the-art hydraulic modelling of urban areas. Here, one-dimensional (1D) hydrodynamic models were chosen to model urban drainage networks and rivers, whereas surface flooding was modelled by 2D hydrodynamic models, with coupling between the 1D and 2D models. The need for high-resolution modelling of megacities was highlighted in July 2012, when large parts of Beijing were flooded. A multi-cell model for Beijing City (with an area of more than 1000 km^2) was developed which was able to reproduce the observed flood pattern while being computationally efficient (Hénonin *et al.,* 2015). Furthermore, progress was made in updating methods for urban flood modelling calibration (Russo et al., 2014), as well as the visualisation of flood model results. The effects of the drivers and pressures were incorporated in the state assessment by producing new models that included the effect of urban growth and climate change. An example of simulated urban growth and subsequent changes in flooding can be seen in Figure 3.



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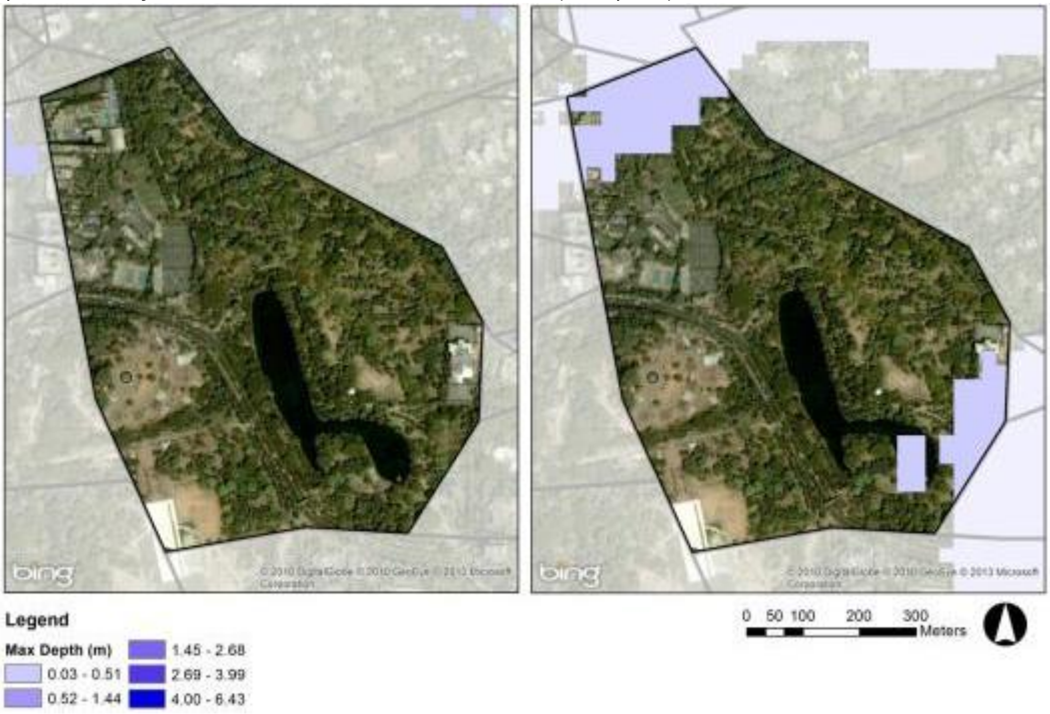

Figure 3. Built-up areas (up) in a catchment and simulated maximum flooding extents (down) for present (left) and future urban growth (right) scenario in Hamburg

3.3 Impacts

In this framework, impacts are considered using the standard approach of distinguishing between direct and indirect impacts, and between tangible and intangible impacts, resulting in four categories of impacts: Direct tangible, Indirect tangible, Direct intangible, and Indirect Intangible (Hammond et al., 2015). In our analysis, we were able to divide them into four simple categories: Direct tangible impacts, including damage to property and infrastructure; indirect tangible impacts such as business interruption; intangible impacts (both direct, and indirect), including health impacts and risk to life, as well as wider psychological effects.

Direct damage to buildings can be computed by overlaying flood maps with building information, and linking them through damage functions. The damage for multiple events with different probabilities was used to calculate the Expected Annual Damage (EAD). City-specific flood depth-damage curves (DDCs) were developed. Where existing functions were unavailable or inappropriate, new functions were developed through field surveys and synthetic approaches, e.g. the FloReTO tool (Manojlovic *et al.,* 2009). A GIS-based flood damage assessment tool was developed (Chen et al., 2016), which computes the flood impact at various spatial scales, using different data formats and resolutions, and a wide range of scenarios of growth and measures. This was challenging because of the large number of buildings involved (over 200,000 in some case studies), and because different flood models use different types of computation grid (either regular grid or unstructured mesh).

Our framework allows for the assessment of indirect tangible impacts, arising from the disruption to business and infrastructure. Models for the assessment of these impacts are still limited, and we were unable to practically implement models. This is an area of growing research (Pregnolato et al., 2017).

The framework was also capable of incorporating intangible impacts of flooding, such as the negative health effects that arise through the mixing of flood waters with wastewater. A methodology was developed for Dhaka, which is beyond the scope of this paper. More information can be found in Mark et al. (2018).

3.4 Responses

In this framework, responses include any measure or action that can be taken in an attempt to improve flood resilience. A review was conducted of all possible mitigation strategies. A methodical framework was established to create a list of measures for consideration. These measures are presented in Table 3 and Table 4. The literature on the types of mitigation measures is extensive, and the details of these measures are not necessary.

We created a feedback here to assess the effectiveness of measures by re-assessing impacts. Two methodologies were applied to estimate the effectiveness of measures. First, a traditional cost-effectiveness analysis considered the capital and operational and maintenance costs compared to the reduction in Expected Annual Damage (EAD) and applying appropriate discount rates to estimate attitudes to future costs and losses (Kull et al., 2013). This approach was applied to the city of Barcelona, to evaluate the effectiveness of structural and non-structural measures (Velasco et al., 2018).

A second approach is to construct a more semi-quantitative Flood Resilience Index (FRI), which can be readily applied to the assessment of less tangible impacts. The FRI represents the overall flood resilience at different urban scales and was calculated for individual buildings and for the whole city. The evaluation of the FRI at the city scale is undertaken through five dimensions (natural, physical, economic, social, and institutional), and combined using a weighted index approach. The dimensions are rated between 1 and 5, representing very low to very high. An example of the FRI for the Raval District of Barcelona is shown in Figure 8 (the same district for which a cost benefit analysis was conducted above). The analysis started with two "business as usual" (BAU) scenarios. These represent pessimistic and optimistic scenarios for climate change and precipitation patterns. They are combined with three adaptation scenarios: (i) non-structural adaptation measures (Adaptation 1 and 4), (ii) Sustainable Drainage Systems (SuDS; Adaptation 2 and 5), (iii) structural measures (Adaptation 3 and 6). This approach has further value as a communication technique (Batica et al., 2018).

Table 3. Portfolio of structural flood response or mitigation measures

<table>
<tr><td rowspan="14">PHYSICAL (STRUCTURAL)</td><td rowspan="11">Adaptation</td><td rowspan="2">Land Management</td><td>Upstream Control</td><td>Reforestation</td></tr>
<tr><td>Restoration of Natural Floodplains</td><td rowspan="13"></td></tr>
<tr><td rowspan="3">Channel Management</td><td>Channel Conveyance / Diversion Channels</td></tr>
<tr><td>Stream Channel Strips</td></tr>
<tr><td>Road System</td></tr>
<tr><td rowspan="6">Coastal Management</td><td>Dikes, embankments, walls</td></tr>
<tr><td>Coastal Alignment</td></tr>
<tr><td>Change of configuration of coastline</td></tr>
<tr><td>Retreat of coastal defences</td></tr>
<tr><td>Offshore barriers, energy converters, wave breakers</td></tr>
<tr><td>Beach nourishment</td></tr>
<tr><td rowspan="3">Water Transfer</td><td rowspan="2">Drainage</td><td>Dual drainage</td></tr>
<tr><td>SuDS</td></tr>
<tr><td colspan="2">Pumping System</td></tr>
</table>

	Resistance	Increase storage capacity	Reservoirs	
			Underground retention	
			Basin or ponds	Dry
				Wet
				Online
				Offline
				Open
				Covered
			Polders	
		Capacity Enhancement of rivers	Dredging	
			Deepening	
			Widening	
			Bypasses	
		Separation of water & population	Dams	
			Dikes, levees, embankments, flood walls	
			Raised infrastructure	
		Architectural planning	Maintenance, repair, retrofitting or reinforcement	
			Flood proofing	Dry
				Wet
	Retreat	Evacuation of human life		
		Evacuation of assets and live stock		
		Retreat of uses		
		Migration	Permanent	
			Temporal or seasonal	
			Relocation	

Table 4. Portfolio of non-structural flood response or mitigation measures

REGULATORY (NON-STRUCTURAL)	**Statutes and Ordinances**	Spatial planning	Land Use Plans	Land use control	
				Zoning	
			Park and forestation plans	Open area preservation and green buffer zone development	
				Waterfront park development	
			Land acquisition and relocation	Land acquisition and development	Public development
					Public/private development
					Sale of development rights
				Land rehabilitation and relocation	Successive residence
					Individual relocation
					Complete relocation
			Urban planning	Building codes	
				Infrastructure building practices	
		Water Management	Flood prevention standards		
			Water circulation plan		
		Environmental Protection	Contract based nature protection/management		
	Stimulation & Compensation	Financial Incentives	Preferential taxation for desired land use		
			Allowances for risk adapted construction or adjustments		
			Reward for accepting occasional or regular water related problems		
		Financial Disincentives	Extra taxation for undesired land use		
			Cutback of insurance payments in case of not compliance with obligation		
			Polluter pays principle		
	Co	Informal Planning			

		Coordination	Knowledge	Scientific
				Local
				Experimental
			Stakeholders	Municipal Authorities
				National Flood Planners
				Emergency response authorities
				Flood managers
				Urban planners
				Civil Engineers
				Water supply and sanitation services
				Civil defense authorities
				Health and Social Services
				Private sector
				General Public
		Information / Dissemination	Public information and education	
			Technology transfer and cooperation	
			Information System Development	
		Warning / Instruction	Flood forecasting systems	
			Warning and evacuation systems	
		Assessments and Monitoring	Risk / Hazard	
			Vulnerability	
			Capacities	
			Hydrological, Meteorological, Geographical, Economic-data	
	Risk & Loss Distribution	Insurance	Traditional	
			Non-traditional	Index based
				Catastrophe bonds
				Micro-insurance
				Gov. Financing instrument

4 Discussion

The enhanced DPSIR framework is a useful approach for structuring and systematizing flood risk management problems, analysing root-causes, the relationships and basic interdependences as well as a logical chain of models. Second, due to its generic nature, the framework can accommodate its application to range of models in various cities. In our application of the framework to central Barcelona, which already has one of the densest urban configurations in Europe, the application of urban growth was not considered as further densification in not possible. In contrast, in Dhaka, urban sprawl is very much a pressing concern, and this pressure was included. More detail on the analyses are found in Velasco et al. (2016) and Khan et al. (2018). An important element of this research is that such frameworks can be applied to developed and developing countries, no matter the state of economic development or urban complexity. The framework also allows for the replacement and improvement of submodels. These could include improvements in the modelling of urban development, flood hazard modelling, and impact assessment.

One theoretical challenge is in discretizing the different elements of the framework. One clear example of this is with climate change, which itself can be broken down into the relationships between economic growth, energy use, emissions and changes in weather patterns. The challenge here is to disentangle these forces and relationships from an inherently complex and messy reality.

Scale problems arise in the development and application of DPSIR frameworks. Cities are both local and global phenomena. They are geographically localised in their extent and are affected by global change such as climate and economic change. In this regard, there is a difficulty for local planners and decision makers to conceptualise or see the value in considering global changes. Beyond this, there is a technical difficulty faced by local users who may not have the technical skills or understanding on how to incorporate global trends to their local situations.

A key challenge was in interlinking the submodels of the framework. For example, linking climate change to flood hazard is a straightforward task, given an estimated increase in extreme rainfall intensity. The methodology adopted a simple method which did not consider relationships between urbanisation and increased risk of extreme rainfall. Linking urban growth with the flood hazard proved more difficult. The nature of the urban growth model is that its expressiveness is limited. Methods to project urban drainage networks into the future are still in their infancy (Urich et al., 2014).

The challenge of integrating the social model was formidable. The effect of risk perception on the willingness for individuals to undertake precautionary measures was not properly integrated into the whole model chain, as a result of the methodological differences (Birkholz et al., 2014). Qualitative elements of the model were notoriously difficult to enter into a framework that seeks to be at least semi-quantitative. In the application of this framework, the FRI was an approach used to overcome this challenge.

Defining the costs and effectiveness of different climate change measures was also a challenge. Describing the costs (construction, and operation and maintenance) of structural measures and the reduction in expected damage is a complex question in itself. Implementing policies such as planning regulations are even more complicated to assess. We were not able to assess any opportunity costs associated with planning policy, which limits the extent to which their true costs and benefits can be assessed.

Perhaps the biggest difficulty was how to practically incorporate feedback into the models. Could development pathways be affected by feedback from extreme events and measures taken to manage risks? The DPSIR framework in its purest form is a linear cause-effect model, and yet while we conceptualised a framework with loops and feedbacks, in our practical experience this was very difficult. Understanding how changes in climate change and flood risk could affect future urban growth or economic change is very limited. The framework was intended as a looped chain, but the complexity and uncertainty increased rapidly as we progressed through the chain.

5 Conclusions

In this paper, we set out an ambitious approach to improve the quality of flood risk management through the application of an enhanced DPSIR framework. We draw the following conclusions.

1. The proposed framework can be used to consistently analyse urban systems and their paths to becoming flood resilient. However, not all the interactions within these systems, and their emergent behaviours can be mapped.
2. Future scenarios should include aspects of socio economic development and plausible climate futures. Those should reflect the state in the future describing the 'business as usual', but also the scenarios containing the flood response measures

3. Urban flood modelling is a well-established methodology, but it requires improvements to simulate floods in mega cities and consider land-use changes as produced by urban growth models. The developed multi-cell approach is promising.
4. Flood impact assessment is a multi-scale procedure that takes different types of floods into account. It should be performed for present and future states and the corresponding damage curves should be adapted to reflect anticipated changes
5. The assessment of the performance of measures should go beyond mere economic factors e.g. cost benefit analysis, which can be supported by the results of implementing the FRI at the case study cities
6. Due to the uncertain future pathways and the limitations of the models, the uncertainties can be high, and these can propagate through the framework chain. However, resilience means functioning under a range of conditions and so resilient strategies should mitigate the influence of uncertainty. In addition, uncertainties imminent in such an approach can be reduced by the regular re-analysis as new information becomes available.
7. The application of the framework is hampered by a lack of understanding of the processes that affect flood risk, and methodologies that can be used to represent these processes. While we can conceptualise the types of models that would fill the gaps, in practice they are either in their infancy, or require data that are not readily available. In this study, we faced this obstacle in many areas, when assessing the impacts of floods on businesses and infrastructure, assessing how economic structural change could affect urban form, and how flood mitigation measures, especially non-structural measures, could reduce flood damage.

It is our hope that this paper will add to the literature on DSPIR approaches to flood risk management, and spur on research to develop improved understanding of the interrelationships and processes, as well as the development of such methodologies to represent these behaviours. Such developments will increase the value of the DPSIR framework.

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